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Comment on "A Coupled Dynamic-Thermodynamic Model of an Ice-Ocean System in the Marginal Ice Zone" by Sirpa Häkkinen

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The recent article by *Häkkinen* [1987] creatively addresses a number of important dynamic and thermodynamic processes in the marginal ice zone (MIZ). We believe that her study will stimulate further research on the coupled ice-ocean system. For now, we would like to offer the following discussion of the need to augment the entrainment equation to include surface buoyancy flux for general application to the MIZ.

INCLUSION OF BUOYANCY FLUX IN ENTRAINMENT FORMULATION

In Häkkinen's study of the coupled ice-ocean system the ocean is considered to have two layers. An essential part of the thermodynamics is the mixed layer entrainment of the lower layer by the surface layer. However, entrainment was parameterized using only the friction velocity at the ocean surface, including an ad hoc *e*-folding depth dependence from *Pollard et al.* [1983]:

$$w_e = 6u_*{}^3 \exp(-h_1/h_0)/(c_m{}^2 + g^*h_1) \tag{1}$$

where h_1 is the upper layer depth, u_* is the water surface friction velocity, g^* is the reduced gravity, h_0 is the length scale for *e*-folding damping, and $C_m{}^2$ is a parameterization for unsteadiness in the turbulent kinetic energy (TKE) budget. The values of h_0 and C_m are specified by Häkkinen to be 20 m and 0.03 m/s, respectively. Equation (1) is insufficient for general application to the MIZ because it does not include buoyant production or damping caused by the buoyancy flux at the ocean surface, B_0. This neglect of the buoyancy flux is inconsistent with the combined contributions to the mixed layer buoyancy that will be associated with the assumed surface heat loss of 500 W/m^2, the assumed evaporation rate of 0.005 m/d, and a predicted freezing rate of about 0.1 m/d. As an example we will provide a one-dimensional evaluation of the heat budget that will demonstrate the need to improve (1).

Including B_0, the recommended form for the entrainment parameterization is

$$w_e = (c_1u_*{}^3 - c_2B_0h_1)/g^*h_1 \tag{2}$$

The value of c_1 is about 2, but it may be reduced for deeper mixed layers (for comprehensive reviews, see *Zilitinkevich et al.* [1979], *Garwood* [1979], *Gaspar* [1987], and *Gallacher* [1987]. In tested [*Martin*, 1985; *Gaspar*, 1987] parameterizations for the net shear production of TKE less dissipation the effective value of c_1 is exponentially reduced on a vertical scale of u_*/f:

$$c_1 \sim 2 \exp(-fh_1/u_*) \tag{3}$$

For Häkkinen's numerical simulation, c_1 would be reduced to about 1. The value of c_2 in (2) is a function of stability. *Stull* [1976] summarizes values of c_2 indicating $c_2 \sim 0.2$ for free convection ($B_0 < 0$ and $u_* \sim 0$). With the strong wind forcing in the Häkkinen simulation, c_2 may be somewhat larger.

For the case of an ocean surface just beginning to freeze (we will assume that the fractional ice cover is initially small) the surface buoyancy flux has three components:

$$B_0 = -\alpha g Q_w/(\rho_w c_p) - \beta g(F - M)(S_1 - S_f) - \beta g(E - P)S_1 \tag{4}$$

Here Q_w is the net heat loss from the water surface, $F - M$ is the freezing rate minus the melting rate, $S_1 - S_f$ is the water surface salinity minus the ice salinity, and $E - P$ is the evaporation rate minus the precipitation rate. To contrast the differences between (1) and (2), we shall compute B_0 and w_e for Häkkinen's simulation of the formation of new ice which occurs in a region that is nearly horizontally homogeneous during the first day [see *Häkkinen*, 1987, Figure 4*c*]. In this region we evaluate (2)–(4) using her values: $E - P = 0.005$ m/d, $F - M = 0.1$ m/d, $S_f = 9.60$ g/kg, $S_1 = 34.60$ g/kg, $S_2 = 34.95$ g/kg, $Q_w = 500$ W/m^2, $h_1 = 75$ m, $T_1 = -1.89$ K, $T_2 = 0$ K, $\alpha = 0.025 \times 10^{-3}$ K^{-1}, $\beta = 0.79$, $f = 1.44 \times 10^{-4}$ s^{-1}, $g = 9.81$ m/s^2, $c_p = 4.186 \times 10^3$ J kg^{-1} K^{-1}, and $\rho_w = 1028$ kg/m^3. We find that

$$\begin{aligned} -c_2B_0h_1 &= 0.2(2.1 + 16.6 + 1.2) \times 10^{-6} \text{ m}^3/\text{s}^3 \\ &= 3.98 \times 10^{-6} \text{ m}^3/\text{s}^3 \end{aligned} \tag{5}$$

for the sum of the surface heat flux, freezing, and evaporation contributions, respectively. Assuming an open water wind stress of 3 dyn/cm^2 (or $u_* = 0.017$ m/s) and assuming that $c_1 = 1$,

$$c_1u_*{}^3 = 5.2 \times 10^{-6} \text{ m}^3/\text{s}^3 \tag{6}$$

The buoyancy jump at the base of the mixed layer (reduced gravity) is

$$g^* = \beta g(S_2 - S_1) - \alpha g(T_2 - T_1) = 2.29 \times 10^{-3} \text{ m/s}^2 \tag{7}$$

Summing the buoyancy flux and the wind-stirring contributions to the entrainment mixing, (2) is used to compute the entrainment heat flux into the surface layer:

$$Q_e = \rho_w c_p \Delta T w_e = 246 \text{ W/m}^2 + 188 \text{ W/m}^2 = 434 \text{ W/m}^2 \tag{8}$$

Conversely, using (1) with an excessively reduced wind mixing and totally neglecting the surface buoyancy flux, we calculate a value for Q_e of only 35 W/m^2. Clearly, the entrainment rate, the heat and salt budgets, and the rate of freezing will be significantly affected by the large entrainment heat flux. The freezing rate predicted by Häkkinen of about 0.1 m/d was dependent upon a net mixed layer heat loss of 465 W/m^2: 500 W/m^2 lost to the atmosphere less 35 W/m^2 gained by entrainment. From the large entrainment heat flux predicted in (8) the net heat lost from the mixed layer should be reduced by about 86%. A slightly greater entrainment heat flux would prevent freezing entirely. However, an important feedback

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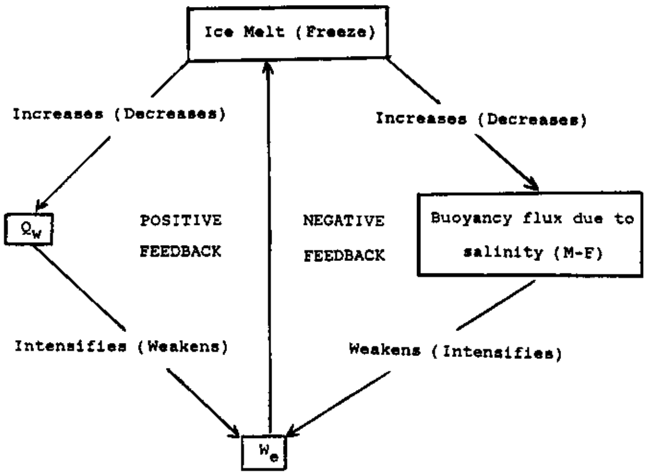

Fig. 1. A positive/negative thermodynamical feedback mechanism in the marginal ice zone.

mechanism cannot be neglected: a reduction in the freezing rate will reduce the upward buoyancy flux due to the downward surface salinity flux. Thus the entrainment rate will not be quite as strong as that computed in (5)–(8). Nevertheless, we recommend that (1) be replaced by (2) in Häkkinen's simulation and in other applications of the complete model.

Buoyant Damping of Mixing

The more general form of the entrainment equation (2) is especially needed when precipitation P and/or melting M are large enough to cause B_0 to be positive (downward buoyancy flux). Neglecting this effect would cause excessive deepening to be predicted. This may explain the need to include an excessive exponential reduction of wind mixing in (1). Alternatively, if the recommended form (2) for the entrainment velocity is used, the wind forcing may be balanced by the buoyant damping, and the mixed layer depth will asymptotically approach a steady state: the Obukhov length scale, i.e.,

$$h_1 \sim c_1 u_*^3 / c B_0 \tag{9}$$

This fundamental process in mixed layer dynamics is not possible with (1).

Feedback Mechanisms

The alternative entrainment parameterization suggested here, equation (2), also implies a positive/negative thermodynamical feedback mechanism in the MIZ, as shown in Figure 1. The positive feedback mechanism is that the increased (decreased) heat loss Q_w due to ice melting (freezing) intensifies (weakens) the entrainment, which further strengthens (decreases) the ice melting (freezing) rate. However, a negative feedback mechanism is that the increased upward (downward) buoyancy flux caused by the salinity flux due to ice melting (freezing) weakens (intensifies) the entrainment, which further decreases (strengthens) the ice melting (freezing) rate.

The thermal expansion coefficient of seawater, α, is very sensitive to temperature and is small at the freezing point. Therefore the negative feedback mechanism mentioned here may be more important, in general, than the positive feedback mechanism.

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